

Thermal Management

LEDs have the potential to operate efficiently for very long lifetimes. There is a proviso on this potential however, and that is that the operating conditions imposed on the LED are conducive to long life.

Two not unrelated factors directly affect the longevity of LEDs, and these are;

- 1) the operating current, and
- 2) The operating temperature of the junction region.

For any given application the current through the LED determines how much heat is generated - all of which must be dissipated. Few, if any, high power LEDs have a primary package which allows them to be operated at full rating, in a normal environment, without some assistance from a secondary heat dissipation system. It is common for the package to be thermally coupled to some form of heatsink which has sufficient surface area to dissipate the heat.

The three means of heat transference are conduction, convection and radiation. When we consider the type of self heating of a solid article that occurs with LEDs, convection is only barely worth a thought. It is restricted to a small amount of air movement near the surface of the device and contributes little. We expect that within the LED thermal system, heat will be transferred from the source to its surroundings (the package and secondary heatsink) by conduction, and that, in a still air environment, heat is lost from the system by radiation.

Because LEDs are small, they can be encapsulated in small packages, however small packages are poor dissipaters of heat, and LEDs generate heat at an extremely high rate. The area of a chip which generates 1watt of heat is about 1mm^2 , so the generation rate of heat is $100\text{w}/\text{cm}^2$. In volumetric terms this is around $10\text{w}/\text{mm}^3$ for a chip that is 0.1mm thick, or $10\text{Kw}/\text{cm}^3$.

In imperial terms this is equivalent to about $160\text{Kw}/\text{in}^3$. If you have a feel for how much power 160Kw is, then you will realise that dissipating this in a single cubic inch of material will make the material very, very hot very, very quickly.

This is only what would happen if the whole concept is scaled up, in reality there is only up to one watt dissipated in a single power LED chip. Although it is only one watt, the surface area that is available to conduct this heat away from the junction is also extremely small. With few, if any, exceptions the cross section that can conduct heat effectively is limited to the backside of each chip. Remembering that the chip is encapsulated in a light transmissive medium, it can be expected that the encapsulation material is a poor conductor of heat.

It is probable that over temperature is the single greatest cause of the catastrophic failure of LEDs. Most manufacturers of LED chips will quote a maximum operating temperature for the junction region of about 130°C . It must be remembered that this is an absolute maximum, and that sustained operation near this value will cause long term damage. A much more realistic design value with scope to accommodate changes of ambient temperature would be around 80°C . This implies that the junction would be 55°C hotter than the air, in a 25°C ambient.

Thermal Conductivity

To minimise the temperature rise of the junction, where the heat is produced, two issues need to be addressed.

Firstly, the ability of the materials in contact with the chip to conduct heat away must be maximised, this requires that they be chosen to have a high value of thermal conductivity. This points directly to metals as the first choice although there are some ceramics and lately plastics which could emerge as alternatives.

And secondly, the surface area to which the heat is conducted must be adequate for transferring the heat into the atmosphere by radiation.

We will not consider forced cooling methods here because all of these techniques consume power which will detract from the wall plug efficiency of the composite system. So the thermal management system consists of a source of heat coupled to a thermally conductive path which truncates at a surface in contact with the atmosphere.

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We can model this on a system which is similar to an electrical circuit, but first we need to define another parameter. One that is derived from Thermal Conductivity (unit W/mK) but which is more practical, and which relates an actual temperature rise to the amount of heat to be dissipated.

I am referring to Thermal Resistance, which has the unit °C/w, and has a value determined by the Thermal Conductivity of the material, the length of the thermal path and the cross section of the path.

This then is a practical parameter rather than a physical constant such as Thermal Conductivity, and it allows the calculation of temperature differences across elements of the thermal path when the input power is known.

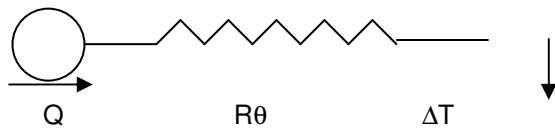
The analogy to an electrical circuit has the following equivalent relationships;

Heat input (in watts, symbol Q) ~ Current

Thermal resistance (°C/w, symbol R θ) ~ Electrical resistance

Temperature difference (°C, symbol ΔT) ~ Voltage

The Ohms law equivalent is $\Delta T = Q \times R\theta$

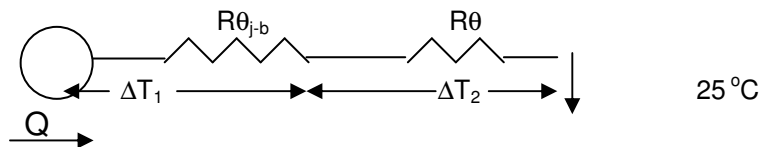


In a practical sense then, the calculation becomes relatively uncomplicated - if R θ is known for the LED device and also for the heatsink or dissipating surface.

Packaged LED devices often have the value published in a data sheet in the form R θ_{j-b} where the subscript "j-b" is intended to represent 'Junction to Board'. So the LED packager tells us what temperature difference to expect between the junction and that area of a mounting board which is adjacent to the device, for each watt of input power.

The total R θ of any system must encompass the complete path from heat source to the air, in a series combination of all the relevant elements, and this includes any stray effects like pressure dependent contact between items in the conduction path.

If we take the value of R θ_{j-b} as a starting point, then by measurement it is simple enough to find an approximate value of R θ for the remainder of the system.



For any value of Q, if we can measure ΔT_2 then,

$$R\theta = Q / \Delta T_2$$

The basic objective of a practical design is to control the value of T_j

$$\text{For any system the absolute value of } T_j (\text{°C}) = \text{Amb.} + \Delta T_1 + \Delta T_2$$

Since ΔT_1 is a fixed value for some value of input power Q, the temperature of the junction is elevated above this, in absolute terms, by an amount equal to ΔT_2 (= Q x R θ).

Two options present here to minimise T_j, reduce Q or reduce R θ .

Reducing R θ will have the correct outcome, and is preferable if conditions allow a satisfactory value to be established.

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Reducing Q however, may be more effective because it affects the value of both ΔT_1 and ΔT_2 .
In all probability some adjustment of both Q and $R\theta$ will give the best outcome.

Example

A practical LED device has a max. input of 10 Watts,
and $R\theta_{j-b} = 5^\circ\text{C/w}$

In a still air ambient of 25°C , ΔT_2 is measured at 50°C
This means that $T_j = 25 + 50 + 50 = 125^\circ\text{C}$

For satisfactory long term operation $T_j = 80^\circ\text{C}$ is a more preferable value

1) Reducing $R\theta$,

requires that the heatsink has $R\theta = 0.5^\circ\text{C/W}$ (10% of the previous value)
thus, $T_j = 25 + 50 + (0.5 \times 10) = 80^\circ\text{C}$

This could be achievable, but in all probability is an unrealistic adjustment to a 'first guess' design, because to a first order approximation, the surface area of the heatsink would be 10x the original area.

2) Reducing Q,

$R\theta_{j-b} + R\theta = 10^\circ\text{C/w}$
 $\Delta T_1 + \Delta T_2 = 80 - 25 = 55^\circ\text{C}$

$$\begin{aligned}\Delta T &= Q(R\theta + R\theta_{j-b}) \\ 55 &= Q \times 10 \\ Q &= 5.5\text{watts}\end{aligned}$$

This is most likely too great a compromise, as the output is reduced by almost half.

3) Reducing both Q and $R\theta$,

by choosing a more achievable reduction of $R\theta$, to say 2.5°C/Watt
 T_j will fall to 100°C . for 10watts input

To further reduce T_j to 80°C , Q must be capped at 7.5watts
 $T_j = (7.5 \times 7.5) + 25$

$$T_j = 81.25^\circ\text{C}$$

4) For an intermediate value of $R\theta$, say 1.5°C/w

T_j will be 90°C for 10watt input.
Q needs to be $(80 - 25) / (5 + 1.5) = 8.5\text{watts}$

$$\begin{aligned}T_j &= (6.5 \times 8.5) + 25 \\ T_j &= 80.25^\circ\text{C}\end{aligned}$$

Reducing the input power is a simple matter of reducing the LED current. Reducing $R\theta$ on the other hand, may be quite difficult in some circumstances.
The most critical factor is the interface between the thermal system and the ambient air. The transfer of heat energy into the air by radiation, is the least effective part of any system and has a direct relationship with the available surface area for any given surface. Put another way, regardless of what the surface is – material, colour, rough/smooth, shiny or dull, $R\theta$ will be reduced if the area is increased.

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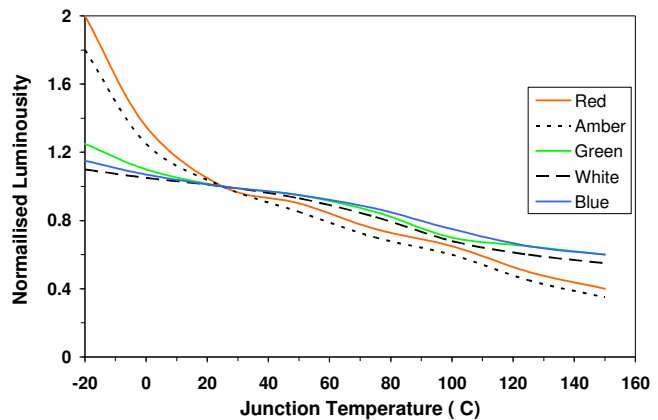
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- A designer can minimise $R\theta$ in the following ways;
- Thermal system is high thermal conductivity materials
 - Maximised surface area
 - Dark external colour – preferably black
 - Smooth, shiny surface

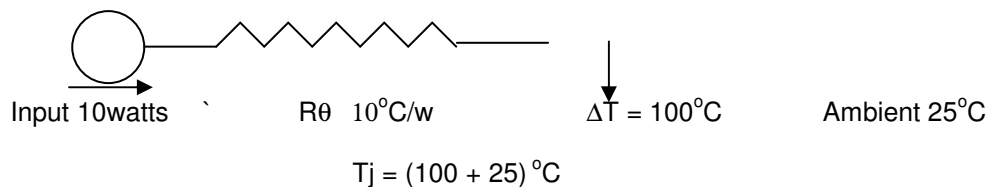
Temperature dependencies

- **OPTICAL OUTPUT**

Of the published data, several parameters have a direct dependence on the junction temperature. The first and most important relationship is the loss of output with elevated temperature. As can be seen from the graph below a quite significant loss of output is expected when the junction is permitted to operate at around 130°C , it can be near to 50%. Even at modest operating temperatures, like 80°C there can be a 20% loss of output, so the aim is to keep the junction as cool as possible, to maximise the output.



For the example below it can be shown that there is little to be gained by driving high output LEDs at the limit of their operating temperature rating.



If the load in the diagram above is blue LEDs, then from the graph we can see that for a junction temperature of 125°C the LED output has fallen to 65%.

By reducing the input power(current) to say 8 Watts, the junction temperature falls to 105°C , and the output rises to 75%.

But this is 75% of only 80% (= 60%), because the output is directly proportional to current which has been reduced by 20%. So the difference in actual light energy generated in this system at 8watts and at 10 watts is only 5% for the additional 2watts of input. Put another way, by increasing the input energy by 20% of rating, the nett gain of output is only 5%.

The preferred action to increase the output(effectiveness) of any system would be to reduce $R\theta$, however In many practical considerations it may not be possible to achieve the optimum value, so the alternative is to reduce the input at only a small penalty.

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- **FORWARD VOLTAGE**

The forward voltage of an LED is also dependant on junction temperature, and has a negative coefficient, meaning that V_f reduces with rising temperature. Where a single device is operating this can be accommodated by controlling the current in the circuit, however if multiple devices are supplied from a single source then unless they are supplied in a series connection there can be unequal current sharing between the parallel paths because of this temperature dependence. In the worst possible case one device will attract the majority of the circuit current in a thermal runaway mode, and be destroyed.

- **DOMINANT WAVELENGTH**

Another parameter which is affected by temperature is the dominant wavelength of an LED. The change is small for the allowable temperature range so that there is an imperceptible change to single colour LEDs.

White conversion by phosphor is a special case where the change can be noticeable. It can be noticed because the phosphor absorption and emission spectra are quite sensitive to the incident wavelength. What this means is that if the wavelength changes by a small amount then the ability of the phosphor to absorb the blue light can be reduced, and since less is absorbed less yellow light is re-emitted, so there is a shift towards the blue colours.

Minimisation of Temperature Rise

The most common means of dissipating heat from a component is by use of a heatsink. Where the total heat to be dissipated is small compared to the surface area and volume of an assembly, and can be identified with a particular component, it is often sufficient to use a local heat spreading heatsink inside an enclosure. Where this is ineffective, components are often mounted on a heatsink that is located outside the enclosure. If the heat cannot effectively escape from the enclosure then the component(s) producing significant heat are relocated on the outside of the enclosure. When enclosing an LED load with significant heat dissipation this is obviously not possible, as in a luminaire for example, so the challenge becomes to make the enclosure itself act like a heatsink.

To dissipate heat from the surface of an enclosure, the enclosure ideally has a surface which is optimised for radiation, is manufactured from material with good thermal conductivity and is configured to have low thermal resistance.

To achieve low thermal resistance the cross-sectional area of a component of the thermal path must be substantial. The process of transferring heat to the outside surface is by conduction so cross-section is important, and the transfer of heat from the surface is by radiation so surface area is paramount.

Plastics are of little use because thermal conductivity is generally poor, and metals will be preferred. This does not mean that plastic material can never be used, but its use will be in a minority.

Radiation of heat from any surface is directly effected by the features of the surface, the surface area available and the temperature difference between the surface and the ambient environment. We shall only deal with still air environments, although to be realistic this must include ambient temperatures of up to 45°C.

The maximum temperature of any thermal system will be found at the source of the heat. If we assume that a device is at rest with all parts cooled to the temperature of the ambient air, then at switch on dissipation commences and the active component heats up. The heat commences to transfer to all parts of the thermal system at a rate which is proportional to the thermal resistance of each part. All temperatures continue to rise until equilibrium is reached when the quantity of energy escaping from the thermal system exactly equals the dissipation inside it. There is an initial warming up period, during which the energy required to raise the temperature of the component parts is being stored. As the warming process proceeds the dissipation rate increases exponentially as the components heat up until the input equals the output, equilibrium is reached and the temperature profile is stable..

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This process always occurs for a naturally cooled system, regardless of the size, mass or thermal conductivity of the system.

How well a surface radiates heat is as much dependent on colour as any other factor. Dark colours are better radiators than bright colours, black is the ultimate, and shiny surfaces are better than dull or matte ones. For a given surface finish and colour, if a system is overheating there are two ways to reduce the temperature, first the input could be reduced, or alternatively the surface area can be increased. It is for this latter reason that commercial heatsinks usually have a thin section finned appearance which maximises the surface area without increasing the size of the footprint.

Thermal Design

The temperature of a heat source in all thermal systems will continue to rise until the equilibrium condition is established. When the heat energy generated in a system is equal to the heat energy lost from the system, the system is considered to be in thermal equilibrium and the temperature of each component will remain steady until something changes to unbalance the energy flow. It is a fundamental practical fact that a temperature difference exists when heat energy is being transferred, just as there must be an electrical potential difference whenever electric current flows in a circuit. The analogy with electrical energy can be extended to suggest that for a given value of current, if the electrical resistance is increased then the potential difference will increase, and in the thermal equivalent, for a given heat input if the thermal resistance increases then the temperature difference across the system will also increase.

To minimise the maximum temperature of a component in a thermal system therefore, we can either reduce the heat being dissipated, or decrease the thermal resistance. In practical situations it is often undesirable to reduce the input power, leaving no alternative other than to decrease the thermal resistance.

In this context the term thermal resistance refers to the total thermal resistance from the heat source to the ambient environment. In the particular case of an LED this means the thermal resistance of the device (usually stated as $R_{\theta j-b}$), plus the thermal resistance of any external heatsink, plus any other influence which could be an enclosure, surround or mounting device - anything which transmits the heat into the surrounding atmosphere.

For an LED device manufacturer, there is a requirement to be able to specify $R_{\theta j-b}$, but all the other influences on overall thermal performance are largely dependent on the design of some end product. These considerations are beyond the scope of supply of an LED device.

When armed with three parameters, a designer of LED products can calculate a good first estimate of thermal performance;

$R_{\theta j-b}$,
the maximum allowable junction temperature and,
total input power

This is sufficient information to enable the calculation of an allowable upper limit of the thermal resistance of the remainder of any physical design. With this information the thermal design can be approximated, however quantifying a theoretical value for R_{θ} may be difficult.

For a conduction path with only one part, a reasonable estimate of thermal resistance can be calculated from thermal conductivity, cross section and path length. It is much more difficult to accurately estimate the effect of surfaces which are clamped together in some way. Surface roughness can result in only point contacts, giving poor conduction between the parts, and the clamping force will also play an important role.

When we come to consider the required surface area for efficient radiation, we can but approximate the effect of the surface finish. As previously mentioned, black is the best colour, what to allow if the colour is brown, or blue ?

How do we quantify the effect of a slightly rough surface ?

What is actually meant by shiny and dull ?

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Generally speaking, when all design considerations have been assessed the thermal design will be finalised largely a trial and error process. Measuring the values of ΔT_1 and ΔT_2 gives a value for T_j and for $R\theta$, from these initial values the design compromises commence.

Derating for elevated ambients

The derating curves below can be used to determine the allowable maximum input of a known thermal system at various ambient temperatures. They also show two limitations for the device they represent, 1) the absolute maximum permissible operating temperature of the junction (130°C in this case) and, 2) we can calculate the thermal resistance ($R\theta_{j-b}$) of the device. Most importantly we can also see directly, what the thermal resistance of the heatsink must be if it is to be effective at some given ambient temperature.

If we assume that the device is rated at 10watts, and has $R\theta_{j-b}$ of $5^\circ\text{C}/\text{watt}$.

Then at an ambient of 25°C , with the device coupled to a heatsink of $6^\circ\text{C}/\text{watt}$ (green curve opposite)

From the curve, for an ambient of 25°C the maximum allowable input power is about 95%

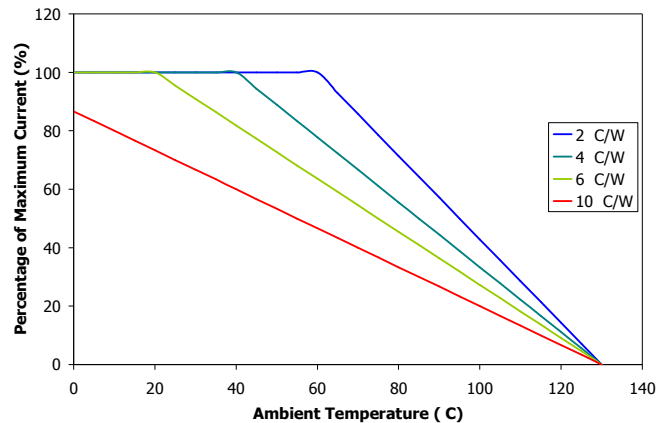
so

$$Q = 9.5\text{watts}$$

$$\Delta T = (5 + 6)9.5$$

$$\Delta T = 104.5$$

$$T_j = 129.5$$



The curves are plotted on the basis that

$$R\theta_{j-b} = 5^\circ\text{C}/\text{watt}$$

and

$$\Delta T(\text{max.}) = 130 - \text{ambient}$$

for 25°C ,

$$\Delta T(\text{max}) = 105^\circ\text{C}$$

If the external heatsink has $R\theta = 6^\circ\text{C}/\text{watt}$,
then

$$Q_{\text{max}} = 105 / (5 + 6)$$

$$= 9.545\text{watts}$$

Conversely, we can calculate that these curves apply to a device which has $R\theta_{j-b} = 5^\circ\text{C}/\text{watt}$.

If we choose an ambient of 60°C , and $R\theta = 6^\circ\text{C}/\text{watt}$

Then,

$$Q_{\text{max}} = 63\% \text{ from the green curve}$$

$$= 6.3\text{watts}$$

$$\Delta T = 130 - 60 = 70^\circ\text{C}$$

$$\Delta T = (R\theta_{j-b} + 6)6.3$$

$$R\theta_{j-b} = (70 - 37.8)/6.3$$

$$= 5.11^\circ\text{C}/\text{watt}$$

The most important conclusion to be drawn from these curves, is that this particular device cannot be operated at max. input in an ambient of 25°C without a heatsink rated at less than $6^\circ\text{C}/\text{watt}$.

This can be seen directly from the curves, and can also be calculated from the known constants ;

$$R\theta_{j-b} = 5^\circ\text{C}/\text{watt}$$

$$R\theta_{b-a} = 6^\circ\text{C}/\text{watt}$$

$$R\theta = 11^\circ\text{C}/\text{watt}$$

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Q = 10watts
 $\Delta T = 110^{\circ}\text{C}$
 in a 25°C ambient $T_j = 135^{\circ}\text{C}$

Thus the curves and the considerations above are applicable to an operating point where the junction is near it's maximum allowable temperature. More prudent designers will aim for a conservative junction temperature. A conservative design can be easily calculated from these curves by imposing a shift on the temperature scale. For a design with 25°C ambient, if we want the junction temperature to remain at 80°C or less we look up the answer at a temperature that is above the actual ambient by an amount equal to the difference between T_j max and T_j design. Since 80°C is 50°C less than the maximum, the design should be calculated using these same derating curves, but at an ambient of 75°C which is 50°C above 25°C . The curves indicate that to impose a junction temperature limit of 80°C in an ambient of 25°C , the maximum input power should be 8watts and the heatsink be rated at $2^{\circ}\text{C}/\text{w}$.

$$\Delta T = 8(5 + 2)$$

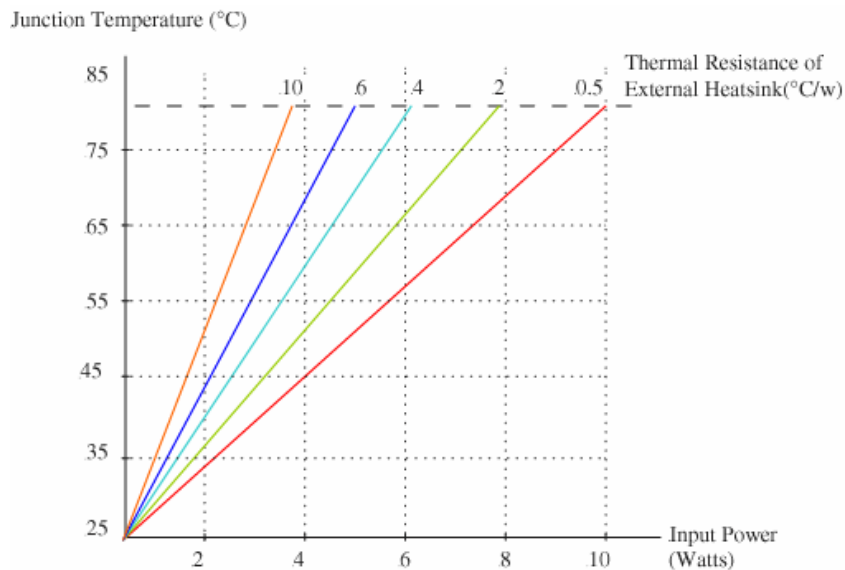
$$T_j = 56 + 25 \sim 81^{\circ}\text{C}$$

These curves are also shown, in snapshot form, in the table below in which the junction temperature is a fixed maximum value of 80°C .

Thermal Resistance of external heatsink $^{\circ}\text{C}/\text{watt}$	Maximum input for $T_j < 80^{\circ}\text{C}$ at various ambients		
	25°C	40°C	55°C
2	7.8	5.7	3.5
4	6.1	4.4	2.7
6	5.0	3.6	2.2
10	3.6	2.6	1.6

Self heating Curves

An alternate way to view thermal performance is by considering the limitations of a fixed environment. The curves below apply to a device operating in still air at an ambient of 25°C , and show the relationship between the allowable input power and the junction temperature (T_j) for systems with various external heatsinks of thermal resistance R_{θ} .



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The system represented by the curves is again a 10watt device with $R_{\theta_{j-b}}$ of $5^{\circ}\text{C}/\text{watt}$. We see again here, that unless the external heatsink has R_{θ} less than $0.5^{\circ}\text{C}/\text{watt}$ then under the stated conditions the device cannot be supplied with maximum input without T_j exceeding 80°C . The curves are drawn on the basis of a fixed ambient, which is the intercept of each curve with the 'Y' axis, and the basic relationship

$$\Delta T = (R_{\theta_{j-b}} + R_{\theta}) Q$$

Since $R_{\theta_{j-b}}$ for the device is known and R_{θ} is specific to each curve,

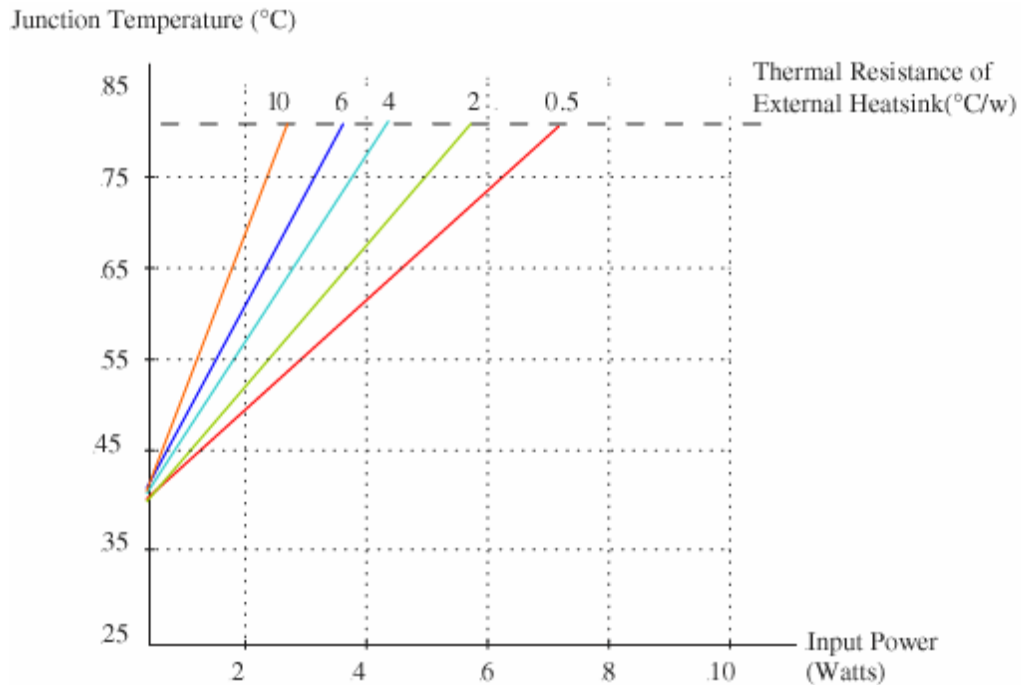
and

$$T_j = \Delta T + \text{Ambient}$$

The allowable input power can be calculated for any value of T_j .

The curves below show what occurs when we plot at a temperature other than 25°C , in the case shown the ambient is assumed to be 40°C .

Any thermal design can be verified with one simple temperature measurement. Once the temperature at the thermal mounting interface of the system (T_b) is known, then T_j can be calculated and so can R_{θ} . T_b refers to the 'temperature of the board' at the point where the device transfers heat to its external heatsink. This can also be considered to be the extremity of the influence of $R_{\theta_{j-b}}$, and the beginning of R_{θ} .



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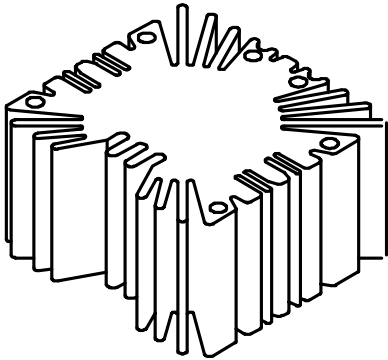
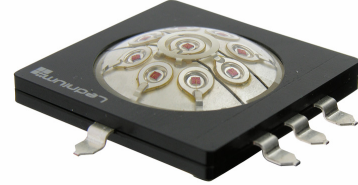
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Practical Example

10watt Lednium Series Device

Specification Data :

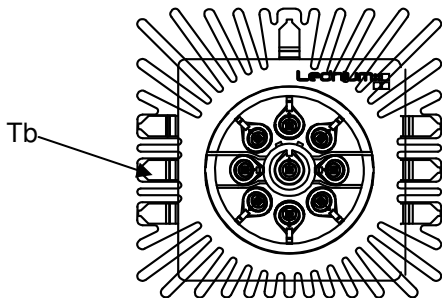
Maximum Power Input 10watts blue, green & white
6watts red & amber
 $R_{\theta j-b}$ 5watts/°C



Heatsink

Dimensions 43 x 45mm(13/4 x 17/8 ")
Length 50mm(2")
Perimeter 650mm(26")
Surface area 325cm² (52 in²) excl. ends.
Material Aluminium
Surface finish Hard Anodising(smooth)

Assembly



1. Device secured to heatsink and the assembly placed on a thermally insulating surface.
2. Input power 10watts
3. Ambient 24 °C in still air

Test Result

$$\begin{aligned} T_b &= 92\text{ }^\circ\text{C}(\text{measured value}) \\ T_j &= T_b + 10(R_{\theta j-b}) = 142\text{ }^\circ\text{C} \\ R_{\theta}(\text{heatsink}) &= (92 - 24)/10 \\ R_{\theta} &= 6.8\text{ }^\circ\text{C/watt} \end{aligned}$$

To achieve $T_j < 80\text{ }^\circ\text{C}$

$$\begin{aligned} Q &= 56/(5 + 6.8) \\ Q &= 4.75\text{watts max. with this heatsink} \end{aligned}$$

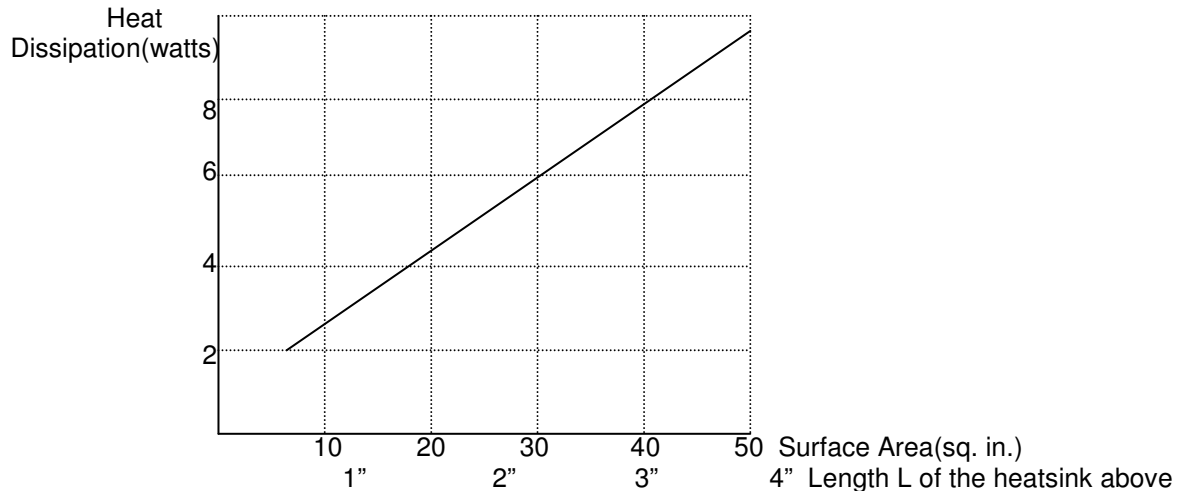
Assuming that there is a straight line relationship between the surface area of a heatsink, and the input heat energy that produces some value of maximum temperature rise on the heatsink surface, we can draw a curve that relates these two variables. It must be noted that close compliance to the curve will only occur for surfaces with very similar colour and smoothness, and that placing the device, complete with heatsink attached to it, inside an enclosure disqualifies all of this data.

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For the heatsink shown above, the curve below would apply to a 10watt device, with $R_{\theta_{j-b}}$ of $5^{\circ}\text{C}/\text{w}$, in an ambient of 25°C in still air and a maximum junction temperature of 80°C .

The 'x axis' is double scaled as 'Surface Area' and 'Length, L', of the heatsink extrusion.



We can calculate that to achieve $T_j < 80^{\circ}\text{C}$ **and** $Q = 10$ watts

Would require a heatsink with $R_{\theta} = 0.6^{\circ}\text{C}/\text{watt}$

From the curve above we can see that this is achieved by this heatsink shape for a length of a little more than 4 inches.

$$\begin{aligned} \text{viz. } Q &= (T_j - \text{Amb}) / (R_{\theta_{j-b}} + R_{\theta}) \\ R_{\theta} &= ((T_j - \text{Amb}) - (Q \times R_{\theta_{j-b}})) / Q \\ R_{\theta} &= (56 - 50) / 10 = 0.6 \end{aligned}$$

For a 6watt device under the same conditions,

$$\begin{aligned} \Delta T &= (5 + 6.8)Q \\ &= 70.8^{\circ}\text{C} \\ T_j &= 94.8^{\circ}\text{C} \end{aligned}$$

For $T_j < 80^{\circ}\text{C}$ **and** 6watt input

$$\begin{aligned} R_{\theta} &= (56 - 30) / 6 \\ &= 4.3^{\circ}\text{C}/\text{watt} \end{aligned}$$

which corresponds to a length of this heatsink, of $2\frac{1}{4}$ inches, and implies an area of similar material of around 60sq. in.